

The rare decay $t \rightarrow c\gamma$ in the General 2HDM type III

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Abstract

We consider the branching ratio for the process $t \rightarrow c\gamma$ in the context of the General Two Higgs Doublet Model type III. We find that taking into account reasonable values for the parameter $\tan\beta$ is possible to get values of this branching ratio up to orders of magnitude lying in the range of sensitivity of near future top quark experiments. For values of $B(t \rightarrow c\gamma) \sim 1 - 9 \times 10^{-5}$, values between 8 – 15 for $\tan\beta$ are allowed.

I. INTRODUCTION

The search for Flavor Changing Neutral (FCN) processes is one of the most interesting possibilities to test the Standard Model (SM), with the potential for either discovering or putting stringent bounds on new physics. In the SM, there are not FCN processes at the tree-level and at one-loop level they are GIM suppressed [1]. For this reason, the branching ratios predicted within the SM for these kind of processes are in general, very small. Special interest has been devoted to the so-called rare top quark decays, e.g. $t \rightarrow c(\gamma, Z, g)$ and $t \rightarrow c(h^0, H^0, A^0)$ [2]. The reason for the interest in these decays is again that the observation of a single event of this kind in near future colliders would imply evidence of new physics which could be related with the Higgs sector of the theory.

In the framework of the SM the decay $t \rightarrow bW$ is by far the dominant one and the rates for the rare decays of the top quark into gauge bosons (γ, Z, g) plus c-quark are too much small. With the current experimental value of the top quark mass, the ratio for $t \rightarrow c\gamma$ is of the order of $\sim 5 \times 10^{-13}$, for the Z^0 boson $\sim 1 \times 10^{-13}$ and for the gluon $\sim 4 \times 10^{-13}$ [3]. These numbers are so tiny because in the SM the FCN decays of the top quark are present at the one loop-level and they are controlled by down-type quarks and are beside strongly suppressed by the GIM mechanism [1].

But some of this undesirable features can change with physics beyond the SM. For instance, there is not any fundamental reason for having only one Higgs doublet. In fact, for two or more scalar doublets, FCN couplings could be generated at tree level unless and *ad hoc* discrete symmetry is imposed [4]. Then it is possible to enhance the branching ratios for rare top quark decays in different kinds of models which include new physics.

Models like Minimal Supersymmetric Standard Model (MSSM) with R-parity, that relax the universality of soft breaking terms with a large flavor mixing only between second and third family can reach values such as $B(t \rightarrow c\gamma(Z)) \sim 10^{-8}$ and $B(t \rightarrow cg) \sim 10^{-6}$ [5]. On the other hand, it is possible to introduce new couplings with R-parity broken and in this context, some of these channels could become observable. For example, very enhanced ratios are predicted in this framework such as $B(t \rightarrow c\gamma) \sim 10^{-5}$, $B(t \rightarrow cZ) \sim 10^{-4}$ and $B(t \rightarrow cg) \sim 10^{-3}$ [6] which could be within the observable threshold of near future experiments. MSSM needs a new Higgs doublet and therefore its Higgs sector is phenomenologically richer. Then, one possibility for new physics is that the electroweak symmetry breaking involves

more than one Higgs doublet and without supersymmetry. In particular, if there is only one extra Higgs doublet, we are in the context of the so-called Two Higgs Doublet Model (2HDM). In such models, a new free parameter $\tan\beta$ arises from the breaking symmetry sector and as we shall see later, it could provide a significant enhancement for the FCN processes. There are three classes of these 2HDM which have been used to examine the ratios for rare top decays, called models I, II and III. The first two are characterized by a discrete symmetry which avoids tree-level FCN processes [4]. In the model type I, one Higgs Doublet provides masses to the up-type and down-type quarks, simultaneously. In the model type II, one Higgs doublet gives masses to the up-type quarks and the other one to the down-type quarks. In models type I and II the corresponding branching fractions for $t \rightarrow c(\gamma, Z, g)$ cannot approach in anyway the detectability threshold reaching only 3-4 orders of magnitude above the SM values [3].

But the discrete symmetry [4] is not compulsory and both doublets may generate the masses of the quarks of up-type and down-type simultaneously, in such case we are in the model type III [10]. It has been used to search for FCNC at the tree level [11], [12]. In next sections we will show that in the context of the general 2HDM type III, the $\tan\beta$ enhancement might be enough to achieve the detectability threshold. Recently, the 2HDM type III has been discussed and classified [13], depending on how the basis for the vacuum expectation values (VEV) are chosen and according to the way in which the flavor mixing matrices are rotated. In brief, the reference [13] considered two cases according to the VEV structure; in the case (a), both Higgs Doublets acquire a VEV, while in the case (b) only one of them gets it. Further, there are two types of rotations which generate four different Lagrangians in the quark sector and two different ones in the leptonic sector. The well known 2HDM types I and II, could be generated from them in the limit in which the mixing vertices at the tree level vanish. In that paper, it has been pointed out that the phenomenology of the 2HDM type III is highly sensitive to the rotation used for the mixing matrices. Also it was shown that case (b) is a particular occurrence of case (a). The model which includes all these features mentioned above, will be called from now on the General Two Higgs Doublet Model (G2HDM) type III. The case (b) is the most familiar in the literature and calculations have been done [11] for the branching fractions of top quark decays. In this particular version of model type III values up to $B(t \rightarrow c\gamma) \sim 10^{-7}$, $B(t \rightarrow cZ) \sim 10^{-6}$ and $B(t \rightarrow cg) \sim 10^{-5}$ are gotten [11].

On the other hand, we must take into account the sensitivity of future experiments to these kind of processes and we must prepare the analysis of the phenomenology in different models in order to distinguish among them in case of a single event detection of this kind. Up to now, CDF has set limits on the FCN decays $t \rightarrow c(g, Z, \gamma)$. In seeking $t \rightarrow Zq$ they looked at $p\bar{p} \rightarrow t\bar{t} \rightarrow qZbW$, $qZbZ \rightarrow ll + 4jets$ with high jet E_T , taking into account the possible background from the SM reactions, they are getting the upper limit $B(t \rightarrow cZ) < 0.33$ at 95% C.L.[8]. To study $t \rightarrow q\gamma$, CDF has examined the reaction $p\bar{p} \rightarrow t\bar{t} \rightarrow Wb\gamma q$. If the W decayed leptonically, the signature would be $\gamma + l + E_T + (\geq 2)$ jets, but if it were hadronically, the signature would be $\gamma + (\geq 4)$ jets with one jet b-tagged. CDF set the 95 % C.L. upper bound $B(t \rightarrow \gamma q) < 0.032$ [8]. Run II will provide much greater sensitivity to these decays, getting to explore ratios up to $B(t \rightarrow q\gamma) \sim 8.4 \times 10^{-5}$ and $B(t \rightarrow Zq) \sim 6.3 \times 10^{-4}$ at $100 fb^{-1}$ of the integrated luminosity [9]. Other analysis for the sensitivity to the FCN decays of top quark have been made for the LHC collider [7]. For $t \rightarrow Zq$, ATLAS collaboration could achieve $B(t \rightarrow Zq) \sim 2 \times 10^{-4}$ at the 5σ level and CMS collaboration up to $B(t \rightarrow Zq) \sim 1.9 \times 10^{-4}$ at the 5σ level, assuming an integrated luminosity of $100 fb^{-1}$. Now, for the decay $t \rightarrow \gamma q(u, c)$, ATLAS could go up to $B(t \rightarrow \gamma q) \sim 10^{-4}$ while CMS about $B(t \rightarrow \gamma q) \sim 3.4 \times 10^{-5}$ at 5σ level.

Our aim is to calculate the branching ratio for $t \rightarrow c\gamma$ in the framework of the most general CP-conserving 2HDM type III, and it shall be shown that in this model is possible to reach the limits of the sensitivity expected in near future top quark experiments. This branching ratio was considered by Atwood, *et. al.* [11] in the 2HDM type III but they choose an specific set of values for the VEV, so that the parameter $\tan\beta$ does not appear in the analysis, which we call case (b). We have shown previously [13] that the CP-conserving 2HDM type III with both VEV different from zero has two interesting features. First, it is possible to generate the Lagrangians for the models type I and II choosing conveniently the basis for the rotation of the mixing matrices in the Higgs sector. Second, in this model appears explicitly the parameter $\tan\beta$ which is the ratio of the vacuum expectation values. Such parameter plays an important role in the phenomenology of the model as we will show in next sections. In fact, this parameter appears as an important one in SUSY versions of the SM in a natural way, and there is not any fundamental reason to avoid its appearance in the 2HDMs type III. In order to give a better presentation we reviewed the general 2HDM type III in section II and then we present the analysis and concluding remarks for the FCN

decays of the top quark in section III.

II. THE GENERAL 2HDM TYPE III

The most general Yukawa's Lagrangian which includes a new Higgs doublet, is as follow

$$\begin{aligned} -\mathcal{L}_Y = & \eta_{ij}^U \overline{Q}_{iL} \tilde{\Phi}_1 U_{jR} + \eta_{ij}^D \overline{Q}_{iL} \Phi_1 D_{jR} + \eta_{ij}^E \overline{l}_{iL} \Phi_1 E_{jR} \\ & + \xi_{ij}^U \overline{Q}_{iL} \tilde{\Phi}_2 U_{jR} + \xi_{ij}^D \overline{Q}_{iL} \Phi_2 D_{jR} + \xi_{ij}^E \overline{l}_{iL} \Phi_2 E_{jR} + h.c. \end{aligned} \quad (1)$$

where $\Phi_{1,2}$ are the Higgs doublets, η_{ij}^0 and ξ_{ij}^0 are non-diagonal 3×3 matrices and i, j are family indices.

In this kind of model (type III), we consider two cases. In the case (a) we assume the VEV as

$$\langle \Phi_1 \rangle_0 = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle \Phi_2 \rangle_0 = \begin{pmatrix} 0 \\ v_2/\sqrt{2} \end{pmatrix}. \quad (2)$$

The mass eigenstates of the scalar fields are given in ref.[14]. The case (b) corresponds to the case in which one of the VEV is equal to zero,

$$\langle \Phi_1 \rangle_0 = \begin{pmatrix} 0 \\ v_1/\sqrt{2} \end{pmatrix}, \quad \langle \Phi_2 \rangle_0 = 0. \quad (3)$$

The mass eigenstate scalar fields in this case are given in ref. [10]. An important difference between both models is that the would-be Goldstone bosons $G_{Z(W)}$ are a linear combination of components of Φ_1 and Φ_2 in the model (a), meanwhile in the model (b) are a component of the doublet Φ_1 [13].

To convert the Lagrangian (2) into mass eigenstates we make the unitary transformations from which we obtain the mass matrices. In the context of case (a)

$$\begin{aligned} M_D^{diag} &= V_L \left[\frac{v_1}{\sqrt{2}} \eta^{D,0} + \frac{v_2}{\sqrt{2}} \xi^{D,0} \right] V_R^\dagger, \\ M_U^{diag} &= T_L \left[\frac{v_1}{\sqrt{2}} \eta^{U,0} + \frac{v_2}{\sqrt{2}} \xi^{U,0} \right] T_R^\dagger. \end{aligned} \quad (4)$$

Where $V_{L(R)}$ and $T_{L(R)}$ rotate down-type quarks and up-type quarks, respectively.

We can solve for $\xi^{D,0}, \xi^{U,0}$ (rotations of type I). Replacing them into (2) the expanded neutral Lagrangian for up and down sectors are

$$-\mathcal{L}_{Y(Q=U,D)}^{(a,I)} = \frac{g}{2M_W \sin \beta} \overline{Q} M_Q^{diag} Q (\sin \alpha H^0 + \cos \alpha h^0)$$

$$\begin{aligned}
& - \frac{1}{\sqrt{2} \sin \beta} \overline{Q} \eta^Q Q \left[\sin(\alpha - \beta) H^0 + \cos(\alpha - \beta) h^0 \right] \\
& \mp \frac{ig \cot \beta}{2M_W} \overline{Q} M_Q^{diag} \gamma_5 Q A^0 \pm \frac{i}{\sqrt{2} \sin \beta} \overline{Q} \eta^Q \gamma_5 Q A^0 \\
& \mp \frac{ig}{2M_W} \overline{Q} M_Q^{diag} \gamma_5 Q G_Z^0
\end{aligned} \tag{5}$$

where $\eta^{U(D)} = T_L(V_L) \eta^{U(D),0} T_R^\dagger(V_R)^\dagger$ and similarly for $\xi^{U(D)}$. The superindex (a, I) refers to the case (a) and rotation type I. It is easy to check that the Lagrangian constructed as $\mathcal{L}_{Y(U)}^{(a,I)} + \mathcal{L}_{Y(D)}^{(a,I)}$ is the Lagrangian of the 2HDM type I [14], plus FC interactions. Moreover,, it is observed that the case (b) in both up and down sectors can be calculated just taking the limit $\tan \beta \rightarrow \infty$.

On the other hand, from (4), we can also solve for $\eta^{D,0}, \eta^{U,0}$ instead of $\xi^{D,0}, \xi^{U,0}$ which we call rotations of type II. Replacing them into (2) the expanded neutral Lagrangian for up and down sectors become

$$\begin{aligned}
- \mathcal{L}_{Y(Q=U,D)}^{(a,II)} &= \frac{g}{2M_W \cos \beta} \overline{Q} M_Q^{diag} Q (\cos \alpha H^0 - \sin \alpha h^0) \\
&+ \frac{1}{\sqrt{2} \cos \beta} \overline{Q} \xi^Q Q \left[\sin(\alpha - \beta) H^0 + \cos(\alpha - \beta) h^0 \right] \\
&\pm \frac{ig \tan \beta}{2M_W} \overline{Q} M_Q^{diag} \gamma_5 Q A^0 \mp \frac{i}{\sqrt{2} \cos \beta} \overline{Q} \xi^Q \gamma_5 Q A^0 \\
&\mp \frac{ig}{2M_W} \overline{Q} M_Q^{diag} \gamma_5 Q G_Z^0.
\end{aligned} \tag{6}$$

In this situation the case (b) is obtained in the limit $\tan \beta \rightarrow 0$. Moreover, the Lagrangian built as $\mathcal{L}_{Y(U)}^{(a,I)} + \mathcal{L}_{Y(D)}^{(a,II)}$ coincides with the one of the 2HDM type II [14], plus some FC interactions. In addition, we can build two additional lagrangians by adding $\mathcal{L}_{Y(U)}^{(a,II)} + \mathcal{L}_{Y(D)}^{(a,II)}$ and $\mathcal{L}_{Y(U)}^{(a,II)} + \mathcal{L}_{Y(D)}^{(a,I)}$. So four different Lagrangians are generated from the case (a). Therefore, with the two Lagrangians (5) and (6) is possible to describe all possible CP conserving neutral current interactions in the quark sector of any model that includes only one extra Higgs doublet as Physics beyond the SM.

III. THE RARE DECAY $t \rightarrow c\gamma$

In the present work, we calculate the branching fraction for the rate of the top quark decay $t \rightarrow c\gamma$ using the model presented in section II. The widths of $t \rightarrow c\gamma$ for the rotations

type I and II are

$$\begin{aligned}
\Gamma^{a,I}(t \rightarrow c\gamma) &= \frac{m_t^3 G_F \alpha_{em}}{1152 \sqrt{2} \pi^4 \sin^4 \beta} \frac{|\eta_{tc}|^2}{\sin^4 \beta} \left| (-\sin \alpha \sin(\alpha - \beta) + \hat{m}_w \eta'_{tt} \sin^2(\alpha - \beta)) F_2(\hat{m}_{H^0}^2) \right. \\
&\quad \left. + (\cos \alpha \cos(\alpha - \beta) + \hat{m}_w \eta'_{tt} \cos^2(\alpha - \beta)) F_2(\hat{m}_{h^0}^2) - (\cos \beta - \hat{m}_w \eta'_{tt}) F_2(\hat{m}_{A^0}^2) \right|^2, \\
\Gamma^{a,II}(t \rightarrow c\gamma) &= \frac{m_t^3 G_F \alpha_{em}}{1152 \sqrt{2} \pi^4 \cos^4 \beta} \frac{|\xi_{tc}|^2}{\cos^4 \beta} \left| (\cos \alpha \sin(\alpha - \beta) + \hat{m}_w \xi'_{tt} \sin^2(\alpha - \beta)) F_2(\hat{m}_{H^0}^2) \right. \\
&\quad \left. + (-\sin \alpha \cos(\alpha - \beta) + \hat{m}_w \xi'_{tt} \cos^2(\alpha - \beta)) F_2(\hat{m}_{h^0}^2) - (\sin \beta + \hat{m}_w \xi'_{tt}) F_2(\hat{m}_{A^0}^2) \right|^2
\end{aligned} \tag{7}$$

where

$$F_2(\hat{m}_h^2) = C_{21}(\hat{m}_h^2) + C_{23}(\hat{m}_h^2) - C_{12}(\hat{m}_h^2) - 2C_{11}(\hat{m}_h^2) \tag{8}$$

with $C_{ij}(\hat{m}_h^2) = C_{ij}(P^2 = \hat{m}_t^2, 0, 0, \hat{m}_t^2, \hat{m}_h^2)$ the Veltman-Passarino integrals and the definitions $\hat{m}_i^2 = m_i^2/m_t^2$, $\eta'(\xi')_{ij} = \eta(\xi)_{ij}/g$.

We have taken into account the contributions due to the diagonal and nondiagonal terms of $\eta(\xi)^{U,D}$ but we parametrize them using the prescription of Cheng and Sher [12], where the FC couplings are proportional to the geometric average of the quark masses, $\eta(\xi)_{ij} \sim g\sqrt{m_i m_j}/2m_W$.

In figure 1, we have plotted the branching ratio $B(t \rightarrow c\gamma)$ for the rotations type I and II. We set $\alpha = 0$, $m_H = m_h$ and m_{A^0} high enough to have only one scalar mass varying in the plot. The plot shows the behaviour with $\tan \beta = 0.1$ (dashed line) for rotation type I and $\tan \beta = 15$ (solid line) for rotation type II. We see that for reasonable values of $\tan \beta$ is possible to reach values in the range of the sensitivity of future top quark experiments. This is because the expressions for the widths in rotation type I and II have a strong dependence on the $\tan \beta$ parameter in such way that in rotation type I we can enhance the branching ratio choosing $\tan \beta$ small and in rotation type II we can do it setting $\tan \beta$ large enough. We also point out that in the case of rotation type II with $\tan \beta = 0$ and $\alpha = 0$ we reproduce the results already obtained by Atwood, et.al. [11].

In figure 2, we have plotted the branching ratio $B(t \rightarrow c\gamma)$ versus α for rotation type II with $m_H = m_h = 150$ GeV and $\tan \beta = 8$. We can see that it is possible to get values of the order of the sensitivity expected by coming soon experiments in top decays $\sim 10^{-5}$ with even lower values of $\tan \beta$. And, in fig. 3 we are showing the lower bounds of $\tan \beta$ in rotation type II according with the value of the scalar Higgs boson mass which are enough to reach the experimental discovery range, *i.e.* for $B(t \rightarrow c\gamma) = 10^{-5}(10^{-4})$ solid line (dashed line).

In conclusion, we can observe that the bounds obtained in this paper are highly sensitive to the type of rotation. Also we might notice that in the 2HDMs type III $\tan\beta$ should be taken into account due to its importance as a free parameter related with the symmetry breaking sector. Instead of that, we are showing that by driving $\tan\beta$ properly, it is possible to enhance the rare branching $B(t \rightarrow c\gamma)$. Further, it is worth to remark that this enhancement in 2HDM type III could also appear in other rare top quark decays $t \rightarrow c(Z \text{ or } g)$, to achieve the corresponding experimental thresholds. Specifically, for values of $B(t \rightarrow c\gamma) \sim 1 - 9 \times 10^{-5}$ which are the orders of sensitivity of the experiments, we get the allowed region $8 \lesssim \tan\beta \lesssim 15$ for rotation type II.

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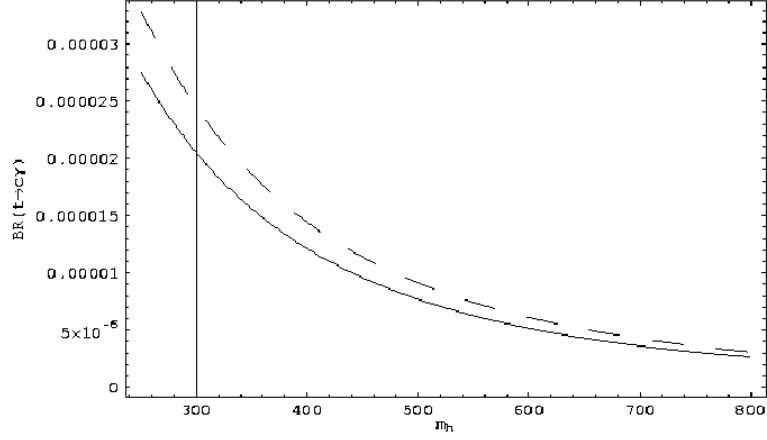


FIG. 1: The branching ratio for $t \rightarrow c\gamma$ for the rotation type I (dashed line) and rotation type II (solid line). Setting $\alpha = 0$, $m_H = m_h$ and m_A decoupled. For rotation type I (II), $\tan\beta = 0.1(15)$. The plot displays that for $m_h \lesssim 300$ GeV, this branching ratio may get the sensitivity threshold for near future top quark experiments under this basic assumptions.

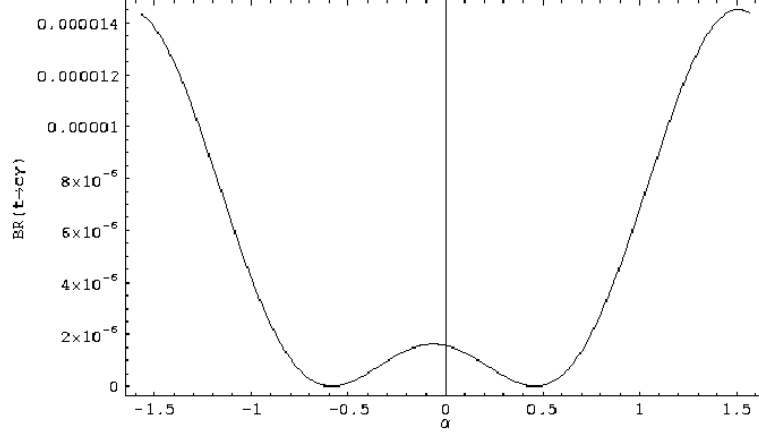


FIG. 2: The $B(t \rightarrow c\gamma)$ as a function of α in the context of rotation type II, for $\tan\beta = 8$, $m_H = m_h = 150$ GeV and m_A decoupled. The range for $B(t \rightarrow c\gamma)$ of 10^{-5} is reached with a lower value of $\tan\beta$.

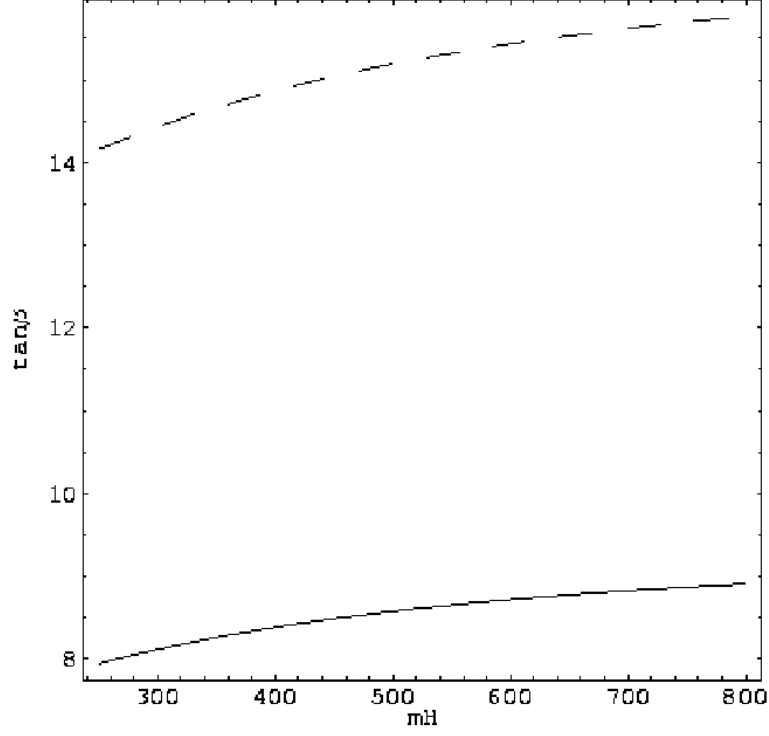


FIG. 3: Contourplot for the $B(t \rightarrow c\gamma) = 10^{-5}(10^{-4})$ solid line (dashed line) in the $\tan\beta - m_H$ plane, for $m_H = m_h$ and $\alpha = 0$. The range for $B(t \rightarrow c\gamma)$ is the range of sensitivity of CMS, CDF, ATLAS experiments in near future.